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Construction possibilities for monolithic concrete spar buoy serial production

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Construction possibilities for monolithic concrete spar buoy serial production

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Abstract. The monolithic nature of Windcrete, that sees floater, transition piece and tower as a single concrete structure, has direct impact on its potential construction process. The large-draft spar-buoy, to be fully completed in a coastal facility, requires horizontal transport that prompts construction also to be done horizontally. Then, the constraints to produce Windcrete structures are: large concrete structure built in horizontal position, preferably in a single monolithic pour with high quality standards, and this within reasonable production time if the project is considered at commercial deployment stage. In search for an appropriate solution, proposals will seek inspiration from a variety of engineering fields: mechanized tunnelling practices, far-reaching adaptations of slip-forming, reinforced centrifugal concrete pipe production and even trenchless technologies such as pipe jacking will all serve as a basis to elaborate a series of tailored solutions compatible with the specific requirements of Windcrete.

1. Introduction

With over 3,589 grid-connected turbines spread over 81 offshore farms in 10 European countries [1], offshore wind is securing its position as one of the fastest growing maritime sectors in the world and contributing to the consolidation of wind energy as a reference source of renewable energy.

Despite the unparalleled success of offshore wind, a series of drawbacks seriously hinder the evolution of traditional bottom fixed turbines: (1) the unsuitability of conventional solutions for many regions with no continental shelf which heavily restricts geographical expansion, (2) the prohibitively high implementation costs of current bottom-fixed technology beyond depths of 60 m and finally (3) market trends showing a noticeable shift towards deeper waters, aggravating the two previous points. These have made evident the need for new solutions and floating support structures are a promising starting point for future designs.

Floating designs are not new as they have flourished with O&G platforms extensively proving at the same time the suitability of concrete to resist harsh offshore conditions. Thus, the idea of adapting floating technology is not in itself unproven but the technical and economic feasibility remain to be demonstrated for offshore wind.

The path that takes Floating Offshore Wind Turbine (FOWT) concepts from a simple sketch to a large-scale project is comprised of several phases that candidate concepts will need to successfully overcome if they aspire to convince the wind industry. The uneven design maturity of floating offshore support structures is enhanced by the fact a wide range of candidate types of floating foundations are currently under consideration. Similar to the case of bottom-fixed offshore turbines, no consensus has been reached on a unique solution and on-going research spreads over three possible floating foundation concepts: spar-buoys, semi-submersible and tension leg platforms (TLP) floaters.

As of today, the most relevant example of spar-buoy is the Hywind Scotland Pilot Project located off the Scottish coast, the only one having reached full-scale deployment making it the world's first floating offshore wind farm [2]. Hywind represents a ground-breaking first step for FOWT consolidation in the wind energy market. However, in terms of construction it provides limited inspiration as it is entirely made out of steel, ruling out similarities in the fabrication process if concrete is used as main construction material. Broadening the scope to bottom-fixed structures is not very helpful either as one finds steel segments clearly dominate current designs too. Thus, to construct the world's first concrete spar-buoy floater, the offshore wind industry will not provide as much inspiration as other civil engineering sectors.

Prior to exploring construction options, the characteristics of Windcrete will be briefly presented together with relevant construction constraints that will drive the project. Aspects concerning logistics and desirable worksite features will follow, finally several possible construction proposals will be described. In search for an appropriate solution, proposals will seek inspiration from a variety of engineering fields: mechanized tunneling practices, far-reaching adaptations of slip-forming, reinforced centrifugal concrete pipe production and even trenchless technologies such as pipe jacking will all serve as a basis to elaborate a series of tailored solutions compatible with the specific requirements of Windcrete.

2. Windcrete, an optimized spar buoy concept

Windcrete is a FOWT spar-buoy concept made entirely out of prestressed concrete developed at the UPC-BarcelonaTech. Its design is based on the detailed hydrodynamic behavior analysis carried out in [3]. The structure presents no joints as floater, transition part and tower are regarded as single continuous piece (Figure 1). By reducing the number of elements to just two single irreducible elements –turbine and support structure–, Windcrete brings offshore wind to its simplest expression. The concept is designed to tackle two of the areas of the supply chain where cost reductions are most likely to be realized: material costs and maintenance costs.

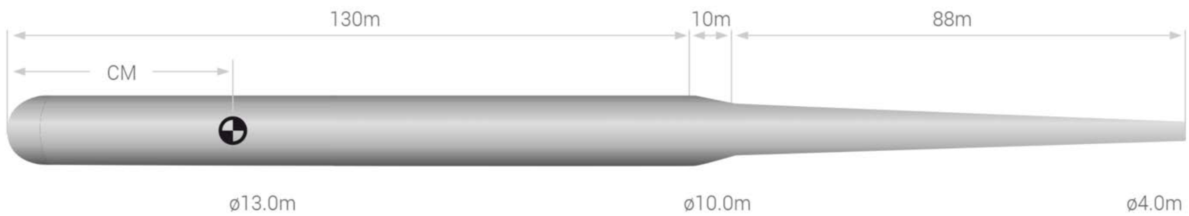

Figure 1. Main dimensions of Windcrete.

The offshore industry is willing to assume greater implementation costs in exchange of generating more energy, turbines up to 15-20 MW rated capacity are expected to enter the offshore wind energy market on the medium- to long-term scale [4]. Mindfully, Windcrete has been conceived as a flexible solution to accommodate larger turbines with minimal design modifications. The present design structural capacity is set to adopt the national renewable energy laboratory (NREL) 5 MW reference wind turbine [5].

Windcrete can, by its very nature be floated directly in a partially commissioned condition towed by tugboats from the out-fitting yard to the offshore site, eliminating expensive heavy-lift vessels from the implementation cycle. The tilting from horizontal to vertical position is shown in sequential order in Figure 2 [3]. Initially the structure is flooded in a controlled manner to its upright position, with around 90% of the structure submerged the installation of the wind turbine is uncomplicated and can be done using a catamaran or similar, in the last phase the structure is erected to the required level above MSL by pumping out water and subsequently ballasted with high density aggregates such as black slag. Further details on the installation procedure can be consulted at *www.windcrete.com.*

A pragmatic attribute inherent to the use of concrete in the marine environment is its excellent durability, capable of cutting down average annual maintenance costs to up to 1/3 compared to steel designs as was found in a study on concrete barges [6]. Also, concrete offers the possibility to extend the design life time from 30 years to 50 or 70 years with little additional cost.

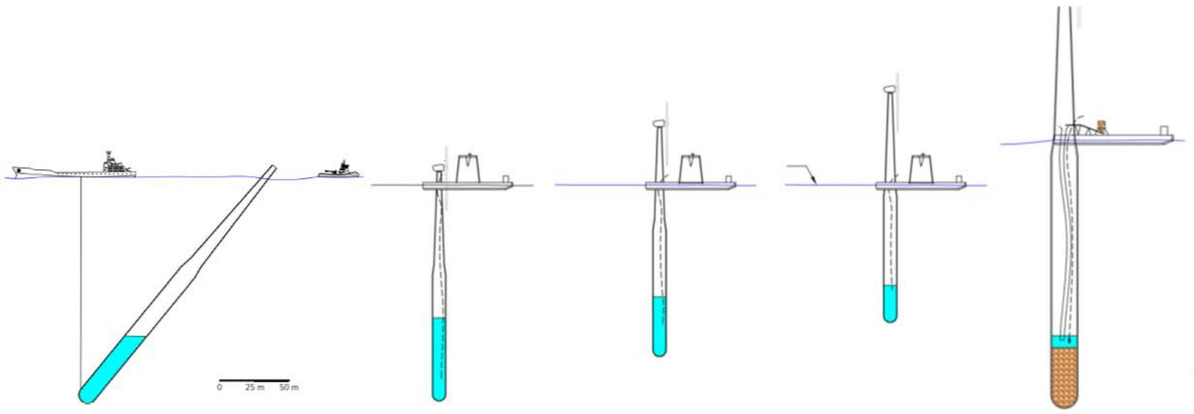

Figure 2. Upending of the platform, turbine installation, erection and ballasting of Windcrete.

Regarding the use of high-strength concrete as main construction material, it is interesting to note that a comparison between a concrete spar and an equivalent steel design was carried out in terms of the material cost [3]. For both structures to withstand the same loads, the steel design amounted to $1{,}98 \cdot 10^6$ kg of steel (3€/kg), whilst the concrete design would require approximately $3\ 500\ m^3$ of concrete (150€/m^3), and 344 630 kg (1,5€/kg), and 260 388 kg (3,6€/kg), of passive and active steel reinforcement respectively. Based on the above standard unitary costs the concrete spar platform was found to be around €2,3 million while the steel solution is around €6,1 million. This study confirmed another known advantage associated to concrete structures: a significant material cost reduction leading to a sharp decrease of CAPEX of up to 60% [3]. Plus, if a monolithic structure is achieved, OPEX can be reduced to a radical minimum making Windcrete a very competitive concept.

3. Construction constraints

Windcrete is a large concrete structure to be built in horizontal position, preferably in a single monolithic pour with high quality standards, and this within reasonable construction time, considering its serial production in the commercial stage. The construction possibilities that emerge from these fairly unusual constraints are incredibly different. One possibility is the use of a specialized slip-former, which may be a reasonable solution to a complex problem, but other possibilities should be considered at least in this preliminary stage.

Due to its size and weight, overall structure is around 230 m and weighs 9,577 tonnes, if one considers a holistic view, Windcrete is not suitable for vertical slip-forming. Unfortunately, the well-known advantages of this technique are offset by a subsequent unpractical handling operation that exceeds the capacity of the most powerful cranes. In fact, any cost-effective construction process will need to minimize handling operations, prompting horizontal construction.

Although the principle of slip-forming the towers should not be abandoned, additional adaptations will be necessary. New methods need to be sought that combine all the desired benefits of slip-forming - maximizing form reuse, minimizing costs and reducing overall project duration- and are compatible with horizontal casting so as to swiftly connect construction and transport phases. The desirable features that an optimal construction process must comply with are: (1) continuous pouring of concrete until the structure is completed, (2) minimum construction time by enabling a repetitive work-cycle that can be

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mechanized with a good degree of automation; and (3) implement an industrialized process that satisfies stringent quality requirements of the finished towers.

Prospective construction proposals should ideally incorporate the above characteristics. Another requirement is maintaining continuity of placement, which is no easy task and calls for meticulous planning and excellent coordination between contractor and concrete supplier. Prior to defining construction methods, several other prerequisites need to be established with regard to worksite features and logistics

- **Construction is to take place at a coastal facility**, ideally in a construction dock, with uncomplicated access to a water depth compatible with the draft of the structure in horizontal (transport) position. After flooding, sufficient pumps must be provided to quickly pump the construction site dry and restart construction. Launching of the structure into the sea is also possible with an appropriate skidding-sliding.
- **Facilities equipped for large-volume non-stop concrete pours**. High rate concrete placement systems (>100 m3/h) will be preferred such as boom pumps, tremies, conveyor belts and direct discharge of mixing trucks to fill the lower part of the section.
- **Concrete supply**. Placing rate will determine the minimum number of concrete plants. Even if the casting rate is within the capacity of a single plant it is recommended to have more than one to ensure continuity of concrete supply even under unexpected events. Concrete plants should be within reasonable distance to site and transport times must be considered during workdays, weekends, both at night and day. Access of mixing trucks within the site to the pouring location should be safe and clear of obstacles.
- **Working around-the-clock** requires sufficient labour be allocated to each stage of the casting process so construction proceeds without interruption. Schedules, lengths of shifts and changeover times must be impeccably planed. Night shifts will require convenient lightning to ensure safe working conditions.
- **Contingency plan.** Any unforeseen event should trigger a quick response plan and be promptly corrected. Back-up equipment must be readily available to resume pouring within minimum delay in the event of failure.
- **Specific travelling formwork.** It is almost impossible to conceive Windcrete construction without prior design and fabrication of appropriate formwork, specifically engineered to that purpose. This formwork system -self-propelled or not- should incorporate the ability of horizontal movement and rely on articulated steel forms. Plus, engineered formwork systems have in-built health and safety features and are very durable if properly maintained.
- **Optimizing form handling.** For large structures, considerable amount of time can be devoted to placing, erecting and stripping of forms, which directly influences delivery time. In serial production of towers, form handling by conventional means may amount to an unacceptable proportion of production time. Mechanizing repetitive activities should be extended to form-related operations too (placing, erecting, treating, cleaning and transport). Mobile equipment should be capable of locking and unlocking forms, lifting them mechanically or by suction and place them in a new position at the construction front where concreting takes place.

These general recommendations should be customary in any cost-effective construction process although specific requirements will surely apply for a particular construction process.

4. Construction proposals

The unresolved construction of Windcrete 'towers' allows ample room to re-think how present civil engineering practices and construction technology can come together to bring forth a set of cost-effective construction methods. Upcoming construction proposals should be seen as a preliminary approach rather than detailed solutions to construction of Windcrete towers, for some creativity played a central role.

Accurately measuring the technical feasibility of untested proposals is very unreliable and results would be subject to personal bias. As no factual basis to support unproven and novel concepts exists, a

Multi Criteria Analysis (MCA) was deemed appropriate to assess construction methods. The MCA is based on a set of features (7), each awarded a numerical score. Features were selected so as to capture and evaluate economic feasibility (Technological readiness, Estimated Economic Feasibility), technical feasibility (execution risk, technological simplicity), productivity (production time, optimized handling operations of the tower during and after construction) and whether a given construction proposal requires major design modifications of the structure as defined in **2.**

Table 1 results from extensive research on construction proposals to achieve Windcrete serial production. A total of 7 construction methods have been selected from a wider range of methods devised from a broad-minded overview of civil engineering practices and readily existing technology [7]. Methods were described in terms of main cost drivers, necessary technology and facilities involved, operative cycles and expected productivity rates. For each proposal recommendations are made on specific lines of research and further technological development.

The selection represents a diverse set of possibilities, some of which are surely not feasible on the short term due to technological gaps. Nonetheless, they have been included if their potential to solve tower construction is believed possible as a result of future research. Table 1. summarizes these seven proposals including their status, execution risk and the inspiring technology.

Table 1. Status, execution risk and inspiring technology of each construction proposal.

PROPOSAL	STATUS	EXECUTION RISK	INSPIRING TECHNOLOGY
TUNNELLING	PROVED	LOW	Tunnel Technology (telescopic formwork)
SEMI-FIXED MOULD	UNPROVED	LOW	New technology
CONCRETE CROWN	UNPROVED	MODERATE-HIGH	New technology
ASSEMBLY-LINE	UNPROVED	MODERATE	New technology
ARCH-TRAVELLERS	UNPROVED	LOW	Tunnel Technology (open-cut methods)
CENTRIFUGING	UNPROVED	MODERATE	Centrifugal Reinforced (Concrete pipes)
INCREMENTAL LAUNCHING	UNPROVED	LOW-MODERATE	Trenchless technology

4.1. Construction proposals based on tunnelling technology.

The tunnel industry provides a set of inspiring ideas that may ease Windcrete construction. It would be wise to assess the suitability of engineered formwork systems currently used by contractors for tunneling projects. In particular, cast-in-place concrete lining has achieved a high degree of mechanization and has allowed for the development of arguably some of the most sophisticated formwork systems. There are two main types of relevant formwork that will be of interest: Travelling Non-telescoping formwork and Travelling Telescoping formwork. The latter is similar to the first but sees an increase of productivity. These formwork systems have preassembled forms mounted on a mobile wheeled frame. The carriage frame serves both as formwork and false work providing all the support during the concreting so forms do not require external anchorage. Hydraulic struts allow hinged sections to collapse once concrete has hardened. Furthermore, the telescopic type is designed so that the back unit can be collapsed and moved forward through the front unit without disturbing it. These travelers support concreting equipment at their core and place concrete radially into forms through series of valves in horizontal layers.

It cannot be stressed enough how fitting these formwork systems are for the needs of Windcrete in terms of productivity and shape produced; they can play a central role in defining a cost-effective construction process. Travelling telescopic and non-telescopic formwork set key features to look for: self-propelled formwork systems that slide on temporary service tracks, support concreting equipment at their core and with the ability to retract-collapse thanks to hinged forms and hydraulic jacks.

4.2. Semi-fixed mould.

This proposal regards formwork more as a fixed steel mold rather than a temporary structure; the bottom half of the cross section is fixed and spans the entire length of the structure while the top half of the cross section are a series of removable arch-forms that are placed and removed by overhead gantry cranes as concrete is placed (Figure 3). This construction method can bypass the need of highly specialized travelling formwork and effectively reduces handling of forms.

The main advantage of this method is its capacity to drastically cut down production time by simultaneous pouring of concrete across the entire length of the structure. By filling the lower half of the mold directly with discharging dumpster or mixing trucks as shown in (Figure 3), this method can be expected to yield highest possible throughput, surpassing productivity of slip-forming methods. The low execution risk and technological simplicity are also valuable factors to look for.

One of the claimed advantages of this proposal is the relative ease with which the finished tower can be un-casted as the semi-fixed bottom half could serve both as a permanent mold and a dry dock at the same time (Figure 4). By minimizing the size of the actual dry dock the time required to pump out the water once it has been flooded, so construction of a new tower can begin promptly.

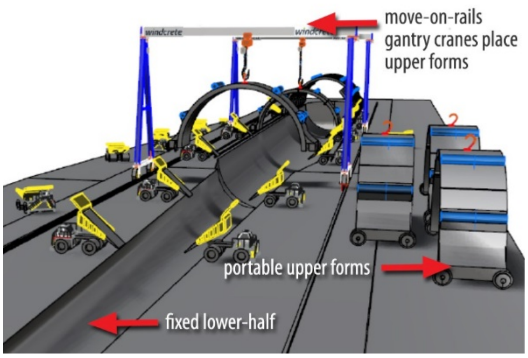

Figure 3. Bird-view of *fixed-mold* with dumpsters discharging concrete.

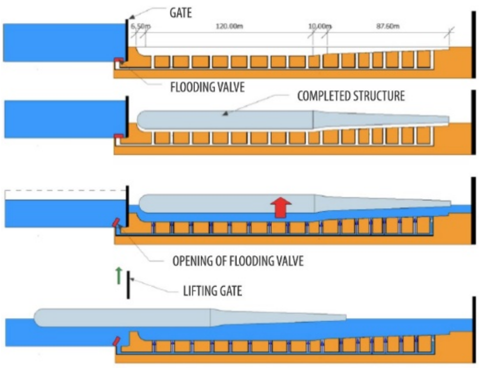

Figure 4. *Fixed-mould* serves both as permanent formwork and dry-dock

4.3. Arch-travellers.

This method sees a series of self-propelled carriages that move on rails parallel to the structure on both sides. Each set of travelers has a distinct function: the leading carriages are external and place forms that operators lock in place, then a concreting device follows either as an external trailing carriage (Figure 5) or an internal concreting train -manned or remotely controlled- slides inside the structure and pours concrete through valves into the previously erected forms, finally another external trailing device retrieves forms when concrete has hardened and brings them to the front of the structure where construction advances to be placed again. The different carriages should slide on separate rails to avoid obstruction between equipment. Minor modifications may be necessary such as providing additional reinforced sections within the tower to support temporary service rails and withstand construction loads exerted by inner travelling equipment.

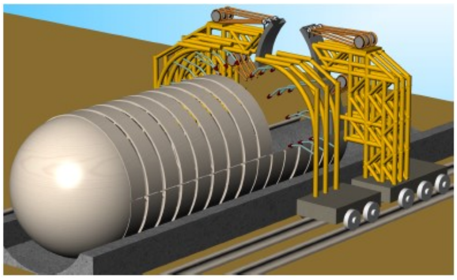

Figure 5. Rear view of arch-traveler with trailing carriage for concreting.

This method understands that large upfront costs to produce specific travelling formwork systems will be assumed in exchange for greater productivity as they are due to pay off on the long run.

4.4. Concrete Crown concept.

This method relies on the design of a highly-specialized concrete distributor able to introduce concrete axially throughout the entire cross-section by means of a circular arrangement of pumps (Figure 6) with high to very-high rate of placement. Horizontal axial placement of concrete is difficult and unstable and will require creating a heap of concrete with a mild slope within the forms so as to provide an adequate base for concrete to fall on. To achieve this slope in concrete, pumping rate should be more intensive at the lower part of the section at the beginning of construction (Figure 7).

The concrete crown will not advance continuously but in discrete steps. Concrete, however, will be placed continuously at a constant rate through foldable pumps sufficiently long to pour into the furthermost part of forms. Logically a new set of empty forms must always be in place before pumps have completely filled previous forms (Figure 7). This requires operators to erect forms while concreting continues uninterrupted. Note that the fact the Concrete Crown advances in discrete steps seems to directly contradict the very nature of slip-forming which involves continuous movement of forms. However horizontal placement is incompatible with continuous movement of forms as unsupported fresh concrete will simply collapse under its own weight, thus it is deemed more convenient to detach forms from the concreting platform –the concrete Crown- so they can stay in place while concrete hardens (Figure 8). If properly executed this method yields an equivalent result to vertical slipforming.

The speed at which the traveler supporting the crown moves backwards should be proportional to the placement rate of pumps and slow enough to guarantee perfect filling with no voids.

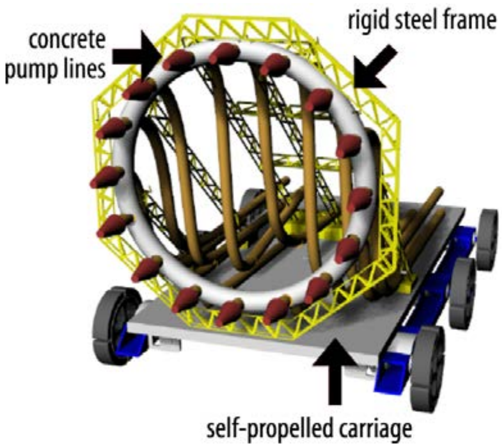

Figure 6. Concrete Crown concept with 16 concreting pump-lines

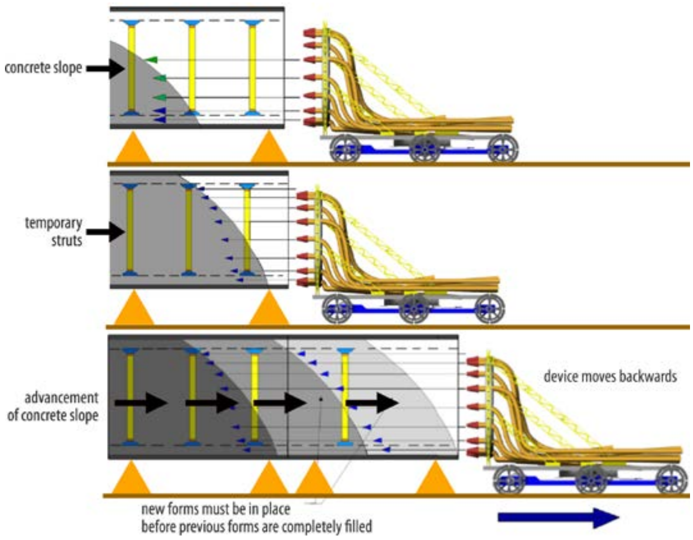

Figure 7. Operative cycle of Concrete Crown.

4.5. Assembly-line.
This method is all about timing and can be regarded as a build and stick approach. The aim is to assemble different ring elements quickly while concrete is still fresh inside the forms. In this proposal, several casting stations produce identical rings in a coordinated manner to join them before concrete hardens. Cold joints will be avoided by planning a well-coordinated “assembly-line system” with staggered production. Staggered production means several rings are produced almost simultaneously with a fixed time lag between the start of two consecutive casting stations.

It is estimated that by subdividing construction into practical smaller “casting units”, more familiar construction practices can be used which in turn will yield cost savings. This segment approach is expected to allow the use of more conventional equipment while obtaining a seemingly monolithic structure. Extra time before concrete sets can be gained by periodically re-vibrating the interface of the concrete to keep it alive [8]. An extra amount of concrete can be pumped radially at the interphases between two connecting rings to further ensure bonding.

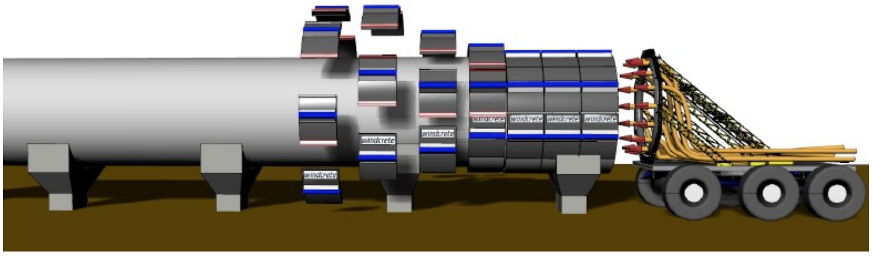

Figure 8. 'Concrete Crown' concept. Forms remain in place for concrete to cure until then cay be stripped, cleaned and replaced at the construction front. Placement rate should be such that a same form can be re-used several times per production cycle.

The main downside of this method is that placing reinforcement is unclear and allowing reinforcement continuity throughout the structure may be difficult. This aspect alone may imply ruling out this proposal. Another drawback is that the success of this construction proposal relies on a tight schedule which makes it extremely time sensible with a relatively high risk of accidental cold joints.

4.6. Centrifugation
Compaction by centrifuging is a widely used technique since the beginning of the 20th century in which a mold is rotated about its axis at high speeds (300 to 3000 rpm). A pre-calculated amount of concrete is fed into the mold and the spinning process forces out water from the mix and compacts the concrete. This construction proposal considers using a process analogous to that used for production of Centrifugal Reinforced Concrete Pipes to fabricate Windcrete towers. Compaction by centrifugation is appealing for several reasons:

- It uses the mould in the horizontal direction
- It is ideal for thin-walled cylinders, otherwise difficult to cast by other means
- Quality of centrifugal concrete is excellent, highly compact with enhanced mechanical properties and resistance to atmospheric corrosion, particularly suitable for watertight structures.
- Compaction by centrifugation requires no inner core significantly reducing the number of form panels which decreases costs.
- It is a quick method allowing for a short delivery time whilst maintaining high quality standards.

This technique to unprecedented dimensions in terms of equipment and energy. Facilities that are able to spin Windcrete’s dimensions would require gears or other spinning devices of remarkable size with lubrication requirements that impose high operating cost per hour. Plus, the technological complexity of the spinning mechanism is high due to the fact that all the gears must be perfectly synchronized. An electrical or mechanical failure could have dire consequences not only for the concrete tower under construction but may also cause substantial damage to the entire facilities in a chain-reaction effect. Thus, centrifuging the entire tower results in an unreasonable execution risk.

If centrifuging is to be adapted to Windcrete, the only realistic application is centrifuging discrete elements separately (Figure 9) which obviously results in a non-monolithic structure with many circumferential construction joints. Besides not satisfying an essential design requirement, the cost of high-quality sealing of joints would need to be valued as well as increased maintenance costs due to the deterioration rate of joints. The energy requirement to spin the mold would also have to be estimated in monetary terms to assess the feasibility of this proposal.

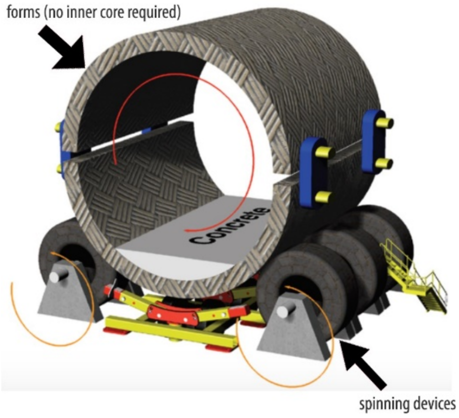

Figure 9. Centrifuging station to produce discrete rings.

Since centrifugal concrete has essentially developed with the fabrication of reinforced concrete pipes, it is a well-established technique for typical pipe dimensions. The real challenge then lies in up-scaling this technique to Windcrete's diameter (13m)

4.7. Incremental launching

The working principle of this proposal is to concentrate all concreting operations at a fixed location (Figure 10) and subsequently launch the structure onto a reception lane as construction progresses. Forms are assembled in ring-shapes; they are then filled with concrete and launched by a circular arrangement of hydraulic jacks pushing directly on the steel forms. A new set of forms are interlocked with the previously launched forms, filled and launched again. Launching can be done smoothly by equipping the lower part of forms with wheels that exactly match rails on the reception lane.

Ring molds must interlock with each other to provide continuity of the mold and allow transmission of the jacking-force from one to another. The diameter of the circular jacking system should be 13.5-14m, approximately matching Windcrete's cross-section although it should be calibrated to the varying cross section of towers.

The idea is extracted from micro-tunneling practices, the difference is that the jacking system does not push prefabricated ring segments into the soil but rather pushes steel ring-forms, previously filled with concrete, into a reception lane shown in Figure 11. The jacks are then retracted and a new mold is introduced and assembled in a ring shape ready for concrete filling. Jacks-will need to gradually apply more pressure to extrude the rings as the structure lengthens as jacks must not only push on the last set of forms but also on all the rings previously launched onto the reception lane. The highest-jacking force will presumably be realized at the end of the process when the almost entire structure has to be pushed. This fully justifies the use of a rail-like system to aid the jacking-system in moving the structure. Additional mechanized systems could help in moving the structure. The configuration of the system should be such that even during the jacking operation there would be no need to stop the concrete pouring avoiding any joints. Additional concrete can be pumped through internal and/or external valves to further ensure bonding between two consecutive interlocking rings.

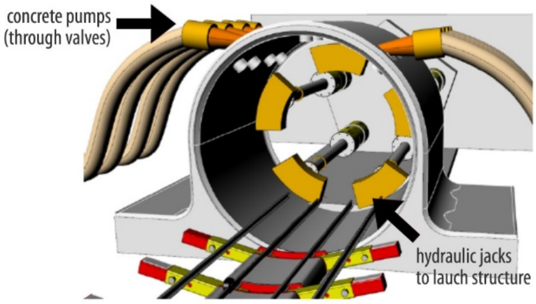

Figure 10. Concreting location with circular arrangement of jacks (retracted). Forms are not shown.

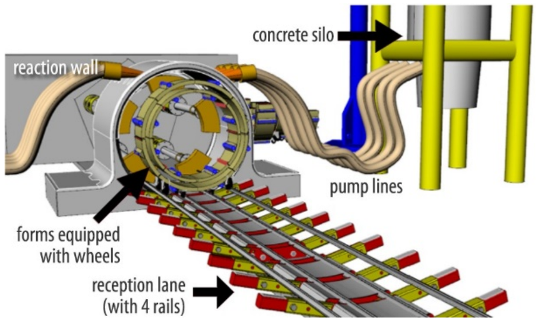

Figure 11. Incremental launching facilities with concreting point, reception lane and first set of wheeled forms in place waiting to be filled by pumps.

5. Comparison of construction proposals

A Multi Criteria Analysis (MCA) is conducted based on seven features, each being appointed a numerical score {0, 1, 2, 3, 4} according to the rating criteria shown in Table 2. The sum of all the individual features gives the overall constructability index (CI) for a particular construction proposal (Table 3). The CI must not be confused with the technical feasibility, but the two are related. The CI is a variable that assesses the capability of a given method to satisfy the specific requirements of Windcrete in terms of serial production, horizontal construction, monolithic nature of the final structure and additional criterions deemed relevant in defining cost-efficiency for spar-buoy production.

Table 2. Rating scheme of relevant features

	0	2	4
Production time	Slow	Moderate	Fast (range of a day)
Execution Risk	High risk	Moderate risk	No execution risk
Technological simplicity	Very high complexity	High complexity	Moderate complexity
Design modifications	Major design modification	Minor design modification	No design modification
Optimized handling	Excessive Handling	Un optimized-normal handling	Optimized handling
(Estimated) Econ. Feasibility	Unreasonably expensive	Feasible	One or more features optimizing costs
Technology readiness	New technology required	Innovation of readily available technology	Minor or no innovation required

Table 3. Constructability index for the seven proposals.

PROPOSAL	Production time	Execution Risk	Techn. simplicity	Design modifications	Optimized Handling operations	(Estimated) Economic Feasibility	Technology Readiness	Constructability index (_ /28)
#1Tunnel technology inspired	3	4	3	2	3	4	4	**23**
#2 semi-fixed mould (*)	4	4	4	4	4	2	4	**26**
#3 concrete crown (**)	1	2	2	4	3	2	0	**14**
#4 assembly-line(**)	4	0	2	0	1	2	2	**11**
#5 arch-travellers	3	4	3	4	3	3	4	**24**
#6 centrifuging(**)	4	4	2	0	2	4	4	**20**
#7 incremental Launching	3	3	2	4	3	3	3	**21**

(*) Economical feasibility requires high structure demand (full-scale commercial deployment stage).
(**)Not feasible on the short term. Unproven technology/uncertain outcome require additional research and extensive testing.

Known technology has been adapted and integrated into tailor-suited construction proposals, some of which have taken the inspiring technology to a whole new level, beyond recognition. Thus, the outcome of most proposals is uncertain and requires in depth analysis which is why the results of this MCA should be treated with care. Tunnel inspired methods and the Arch-travellers rank high, only surpassed by the fixed mould approach due to its technological simplicity and low executional risk. On the other hand, innovative methods such as the assembly-line and the 'Concrete Crown' are appointed the lowest C.I due to the unproven nature of the technology involved, which require additional research, and the relatively high risk of cold joints occurring during the process.

For this preliminary comparison, all the weights of the considered features have been set equal to 1. This translates in assigning equal importance to all features which is not necessarily correct, leading to disproportionate results that do not capture important particularities of some proposals. For instance, designs modifications can be beneficial if they lead to a significant cost- reduction, however in this MCA changes in design have been severely penalized.

To obtain a more reliable result, it would be interesting to perform a sensitivity analysis to assess the relative influence of each of the chosen features on the C.I and help determine whether a different set of features will be better at predicting the constructability of Windcrete.

6. Conclusions

An extensive overview that covered a wide range of civil engineering fields found that technologies to simultaneously meet all the construction constraints of the project require some degree of adaptation.

Proposals followed four distinct logics: proposals based on minor adaptations of current technology (inspired from tunnelling practices such as telescopic travelling formwork and arch-travellers), proposals based on up-scaling existing technology (centrifuging), proposals based on modifying the original use of a given technology and give it a new purpose (incremental launching), and proposals based on innovation (Concrete crown, assembly-line or semi-fixed mould). Any given proposal is associated to a unique casting facility with singular requirements with regard to space and technology. Ideally, the construction process needs to be industrialized as much as possible to standardize and speed up production, ruling out traditional formwork which is labour intensive and time consuming.

Tunnel equipment is a reasonable starting point (yields similar cross-section and highly mechanized) with key features to include: self-propelled formwork systems moving on temporary service tracks that also serve as falsework, support concrete distributor systems and can retract-collapse to cast sections with certain ease thanks to hinged forms and hydraulic jacks.

Generally speaking, tunnel inspired methods were awarded highest C.I and may be seen as the most suitable (Table 3) as they will require the lowest adaptation when compared to technologies from other fields. However, besides adapting certain proven techniques, which will always lead to adaptation costs, it is worth considering to reallocate some of these resources to develop new technologies through innovation, rather than adaptation. Costs of heavily adapting current technology should be compared with the costs of research and development of new technologies. More complex adaptations or investment on novel technologies may be justified in exchange for a significant increase in productivity. The main disadvantage of innovative approaches is that they present increased technical risks during execution. Risks, however, can be expected to decrease as construction experience increases.

Upfront costs to construct facilities and develop necessary technology, delivery time, risk of joints, degree of automation, and optimized handling of forms and of the finished structure are the main aspects driving a cost-efficient construction method. Windcrete's unique construction constraints can play a special role in creating value, as drivers of discovery and invention.

Windcrete has the potential to increase the design service life time of the support structure whilst reducing material costs, offering a cost-effective installation process and a practically maintenance-free design. This series of cost advantages – decrease of CAPEX and OPEX- can help offset the technical complexity of building a monolithic spar-buoy horizontally by justifying large investments on specific technology to optimize platform production at commercial stage.

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